Method of determining a structure of a moving object

The present invention relates to the field of digital imaging. In particular, the present invention relates to a method of determining a structure of a moving object from an at least two dimensional data set, an image processing device and a computer program for an image processing device.

The anatomy of the human coronary tree is widely consistent between normal subjects. It always consists of three main branches called left anterior descending (LAD), left circumflex (LCX) and right coronary artery (RCA). The main variation in topology to be found is a dominance of either left or right branch supplying the apex of the heart, as described in M.D. Cerqueira et al. "Standardized Myocardial Segmentation and Nomenclature for Tomographic Imaging of the Heart" Circultation 105: 539-542, 2002 which is hereby incorporated by reference, attaching more sub-branches to either side. Geometric properties of segments, however, may vary significantly between subjects, for example, due to differences in size and shape of the ventricles of the heart.

Document C. Chalopin, I.E. Magnin, G. Finet "Automatic labeling of the coronary tree using a three-dimensional reference prior Model" Computers in Cardiology 25, p. 761-764.1998 discloses the generation of two dimensional reference models of either left or right coronary tree from a given three-dimensional model, each of which having a different projection angle. The best fitting reference model is used to identify a coronary main branch in geographic projections and to label the segments of the image. In other words, the best fitting reference model is used to identify the respective branches of the human coronary tree in an image.

It is an object of the present invention to provide for an improved prediction of properties of a moving object such as, for example, the human heart.

The above object may be solved by a method of determining a structure of a moving object from an at least two-dimensional data set according to claim 1.

According to this method, a model of the structure relating to the properties of interest is applied to the data set. Then, an adaptation of the model to the data set is performed. Then, on the basis of the adapted model, a location of at least one portion of the structure of the moving object is estimated.

In other words, with respect to the example of the coronary tree of a human heart, a model of the coronary tree, which is, for example, a statistic deformable model based on preceding measurements, is applied to, for example, a two-dimensional image, such as an x-ray angiography image. Then, this model, which may be a three-dimensional model, is adapted to the two-dimensional image representing the data set. This adaptation may, for example, be performed by a parameter variation. Then, a location of at least one portion of the structure, for example of a portion of the coronary artery with a total occlusion, which renders the vessel invisible, since no contrast agent is supplied to this region, is predicted by using the adapted model.

Advantageously, this exemplary embodiment of the present invention may allow for improved diagnostics of, for example, occlusions in the artery tree or an improved detection of side branches of the coronary tree, since, on the basis of the model, a location of at least one portion of the coronary tree or the artery tree may be predicted.

According to another exemplary embodiment of the present invention as set forth in claim 2, the adapted model is overlaid onto the image of the coronary tree such that an image may be displayed showing the actual measured image and the overlaid model, such that it can easily be determined where a vessel such as a lumen should be and whether it is not visible due to, for example, an occlusion, or where, for example, a side branch of the lumen may be expected. This may allow, for example, for improved catheter intervention.

According to another exemplary embodiment of the present invention as set forth in claim 3, parameters of the model are adapted on the basis of a similarity of the model to the structure, which may allow for a simple and efficient adaptation of the model.

According to another exemplary embodiment of the present invention as set forth in claim 4, an image quality of an image displayed may be improved by superimposing images of the object of interest taken at different points in time or with

different projections. For superimposing images taken at different points in time or projections, the adapted model may be used as a reference, allowing for a registration of these images.

According to another exemplary embodiment of the present invention as set forth in claim 5, the model is a deformable model and the adaptation of the model is performed by an energy minimization of an internal and an external energy of the model, which allows for a fast adaptation of the model.

According to another exemplary embodiment of the present invention as set forth in claim 6, the model is a statistical model of a coronary tree of a human heart and the data set relates to x-ray angiography data.

According to another exemplary embodiment of the present invention as set forth in claim 7, an image processing device is provided, allowing to estimate a location of at least one portion of a structure of an object of interest, which, for example, is not discernible in an image representing a two-dimensional data set. This estimation is performed on the basis of a model of the structure of interest adapted to the image, i.e. the data set.

Further exemplary embodiments of the image processing device are provided in claims 8 and 9.

According to another exemplary embodiment of the present invention as set forth in claim 9, a computer program is provided allowing for an estimation of a location of at least one portion of a structure of a moving object of interest by using a model of the structure of interest adapted to the measured data set. The computer program may be written in any suitable programming language, such as C++ and may be stored on a computer readable medium, such as a CD-ROM. However, the computer program according to the present invention may also be presented over a network such as the WorldWideWeb, from which it may be downloaded into the working memory of a processor.

It may be seen as the gist of an exemplary embodiment of the present invention that a location of a portion of a structure on or of a moving object, which, for example, is not discernible in an image representing the original measured data set is predicted by using a model adaptation. For this, a model of the structure of interest is adapted to the structure of interest in the original data set. Once the model is adapted to

the image, portions (a location, a dimension or a direction thereof) of the structure not discernible or visible in the original measured image may be indicated by the model which may be displayed in an overlaid fashion on, for example, a display.

These and other aspects of the present invention will become apparent from and elucidated with reference to the embodiments described hereinafter.

Exemplary embodiments of the present invention will be described in the following, with reference to the following drawings:

Fig. 1 shows a schematic representation of an image processing device according to an exemplary embodiment of the present invention, adapted to execute a method according to an exemplary embodiment of the present invention.

Fig. 2 shows a flow-chart of an exemplary embodiment of a method according to the present invention.

Fig. 3 shows a schematic representation of a coronary model according to an exemplary embodiment of the present invention.

Fig. 4 shows a projection of a geometric coronary mean model with branches corresponding to Fig. 3 according to an exemplary embodiment of the present invention.

Fig. 5 shows a sub-set of branches overlaid on an image and a corresponding area at a well-fitted model, according to an exemplary embodiment of the present invention.

Fig. 6 shows a flow-chart of another exemplary embodiment of a method according to the present invention.

Fig. 7 shows images of a coronary vessel tree generated in accordance with the present invention.

Fig. 8 shows a flow-chart of another exemplary embodiment of a method according to the present invention.

Fig. 1 shows a simplified schematic representation of an exemplary

embodiment of an image processing device in accordance with the present invention. In Fig. 1, there is shown a central processing unit (CPU) or image processor 1 for applying a model of the structure of interest to the original measured data set, for performing an adaptation of the model to the data set and for performing an estimation of a location of at least one portion of the structure by using the adapted model. The image processor 1 is connected to a memory 1 for storing the data set, for example, a plurality of images relating to x-ray angiography images. The image processor 1 may be connected by a bus-system 3 to a plurality of periphery devices or input/output devices which are not depicted in Fig. 1. For example, the image processor 1 may be connected to an x-ray scanner. However, the image processor 1 may also be connected to an MR device, to a CT device, to an ultrasonic scanner, to a plotter or a printer or the like via the bus-system 3. Furthermore, the image processor 1 is connected to a display such as a computer screen 4, for outputting information and/or images to a user. Furthermore, a keyboard 5 is provided, connected to the image processor 1, by which a user or operator may interact with the image processor 1 or may input data necessary or desired for the segmentation process.

Fig. 2 shows a flow-chart of an exemplary embodiment of method according to the present invention, which may be used for operating the image processing device depicted in Fig. 1.

In the following, the present invention will be described with respect to the determination of the anatomy of the human coronary artery tree. In this connection, the present invention is particularly suited to improving and speeding up the diagnostics of coronary artery defects and their treatment. Thus, for example, the present invention may be applied as an intervention support system for 2D-3D x-ray angiography. Also, the present invention may be applied in conjunction with catheter intervention.

As may be taken from Fig. 2, in step S1, an image is acquired, for example, by x-ray angiography. This image may relate to a particular phase of the heart and to a particular projection angle. Then, in step S2, the model, which may for example be a statistic model projected into the plane of the image, is used to measure a distance between parts of the model projected into the plane of the image and corresponding structures in the image. This distance measured in step S2 is used to determine a similarity value in step S3, reflecting a similarity of the coronary artery tree

depicted in the image and the model to be adapted to the actually measured coronary artery tree in the image. In case it is determined that the similarity in step S3 is lower than a pre-set threshold value, the method continues to step S4. In case it is determined in step S3 that the similarity is above the pre-set threshold value, the processing ends and the image may be displayed to a user in a fashion where the adapted model is overlaid onto the image, allowing that the user recognizes where, for example, a side branch of an artery is to be expected or where, for example, a branch of an artery should be. In case the model, for example, indicated that there should be an artery portion, but in the actually measured image there is no artery portion, the user may assume that, for example, there may be an occlusion in the artery, such that no contrast fluid in the blood makes the artery visible in this region.

As may be taken from steps S4 and S5, parameters of the model are varied. Then, as may in particular be taken from S5, positions and connections of the model may be varied and parameters such as heart phase φ, the projection angle p of the model and an individual derivation from the mean model given by φ and p may be varied, which is indicated in step S6, allows a prediction of model positions by calculating a projection of model positions. In other words, in step S6, the three-dimensional model varied and adapted in the preceding steps, is projected into the image plane of the image acquired in step S1. Then, as indicated in step S7, the projected image is used to re-enter the iteration in step S2.

The coronary model used according to an exemplary embodiment of the present invention may, for example, be taken from Figs. 3 and 4. Fig. 3 shows a schematic coronary model (topology only) with LAD, LCX and RCA as well as some sub-segments according to an exemplary embodiment of the present invention. Fig. 4 shows a projection of the geometric coronary mean model with branches corresponding to Fig. 1 according to an exemplary embodiment of the present invention, as it may be achieved in step S7.

The geometry of each branch of the geometry model is represented parametrically in such way that it expresses the position of a branch both in global and local coordinates. In the local coordinates, the position of a branch is defined relative to another branch, for example, to a parent branch. The parameters of the model are modeled statistically such that a given parameter setting is assigned a probability value.

A specific potential geometry of the coronary tree, as indicated in steps S2 to S7 in Fig. 2 may be predicted by a parameter setting. Movement and deformation of the branches caused by heartbeat and by respiration are covered by the model. For the heartbeat, this means that geometry predictions are possible for any heart phase. To illustrate the use of the coronary model in more practical terms, an exemplary embodiment of a parameterization and a sampling is described in the following.

According to this exemplary embodiment of the present invention, each branch is assigned a set of sample positions $s_{b,i}$. Each branch b is interpolated through its sampled position s_{bn} by a spline. The model holds a statistical description of reached sample position, for example, a mean value $\hat{s}_{bi}$ and covariance matrix. These values may be referenced to a global coordinate system, or they may be positioned relative to the corresponding parent branch (i.e. global or local coordinates). Also, information about lumen diameter of each branch may be provided by the model by l_{bi}. The deformation of the coronary tree is covered by a variation of sample positions over the heart cycle $\varphi = 0..2\pi$. Similar to the spatial sampling by sample positions, some temporal samples $s_{b,i,t}$ with $t=1..m$ are part of the model, where a temporal interpolation of the distribution of positions is provided between the m temporal samples. Thus, the model according to this exemplary embodiment of the present invention may be used to predict the position of each branch b at a given heart phase φ by a statistical description of the sample positions $\hat{s}_{b,l,\phi}$ and by spatial spline interpolation. This will be described in further detail in the following.

For a given heart phase φ_g and a given projection plane orientation p_g, the projection of the mean model $P_{\hat{s}}(\phi_g, p_g)$ may be calculated by

$$P_{\hat{s}}(\phi_g, p_g) = \{ \hat{s}_{b,l,\phi_g} \cdot M_{p_g} \}$$

where M_{p_g} is the matrix that projects a point onto the plane with orientation p_g.

Fig. 4 shows such a projection using an orientation similar to the schematic view in Fig. 3. This simulated projection may be overlaid to an angiographic image as indicated above.

However, individual properties of the patient's heart may deviate from

the mean model $\hat{s}_{b,l,\phi_g}$. Also the given parameters like the projection orientation p_g or especially the heart phase φ_g may not precisely reflect the image acquisition situation. Thus, the model should be allowed to warp itself in order to find a good congruence between model branches and visible branch position in the angiographic image.

According to an exemplary embodiment of the present invention, this may be done by applying a deformable model approach where the model parameters s_{b,l,ϕ_m}, φ_m, and p_m are varied to optimize a similarity measure $\sigma = d_m + f_m(I)$ (see steps S2 S3 in Fig. 2).

This similarity measure may be given by an image feature term $f_m(I)$ which determines how good the projected model branch positions agree with features in the image that correspond to coronaries (see step S2 in Fig. 2). A good proposal for $f_m(I)$ is a measure of the directed gradient at the predicted vessel boundaries. It gives a maximum value, when predicted coronary positions in the projection coincide with real vessel walls in the image of the original data set. At both sides of the spline through all sample projections of a given branch $P_s(\phi_g, p_g) = \{ s_{b_g,l,\phi_g} \cdot M_{p_g} \}$ and with a distance $l_{bg,i}$ to it, a strong image gradient orthogonal to this line is expected. It is measured at a couple of sample points and all values may be averaged.

According to another exemplary embodiment of the present invention, $f_m(I)$ corresponds to the sum of gray values within the area of all predicted projected coronaries, assuming that coronaries appear bright in the image. For each position in $P_s(\phi_g, p_g) = \{ s_{b,l,\phi_g} \cdot M_{p_g} \}$ given by the actual parameter setting of the model, a circular area $C_{b,i}$ with diameter $l_{b,i}$ is taken. The unification of all areas U may be given by $U = \sum_{b,l} C_{b,l}$. The average image intensity on this selected part of the image yields the feature term

$$f_{grey} = \frac{\int_U I(x)\,dx}{\int_U 1\,dx}.$$

Fig. 5 shows a sub-set of P_s overlaid on the image and the corresponding area U (union of circular areas) at a well-fitted model in accordance with an exemplary embodiment of the present invention. As may be taken from Fig. 5, Fig. 5 shows an

example of the area U where the image intensity is measured. By using, for example, steerable filters on the image at the modeled position, both image gray value properties and image gradient properties may be combined. However, as a downside, using such steerable filters increases computational efforts required.

The distance measure d_m of the parameter setting to the modeled distribution is considered in the similarity measure. There must be distance measures for each parameter or parameter set:

$$d_s\left(s_{b,l,\phi_m}\right)=\left\|s_{b,l,\phi_m}-\hat{s}_{b,l,\phi_g}\right\|$$

for each b and each i,

$$d_\phi(\phi_m)=\left\|\phi_m-\phi_g\right\|,$$

and

$$d_p(p_m)=\left\|p_m-p_g\right\|$$

where $\|x\|$ is a suitable distance measure in the domain of the parameter. As the model holds a distribution $d_{s_{b,l,\phi_g}}$ for each parameter s_{b,l,ϕ_g} also a statistical distance measure (e.g. Mahalanobis distance that also considers the covariance matrix) is applicable. A weighted sum of the three single distance measures is used as distance measure of the model parameters to the expected parameter setting

$$d_m=w_s\cdot\sum_{b,l}d_s\left(s_{b,l,\phi_m}\right)+w_\phi\cdot d_\phi(\phi_m)+w_p\cdot d_p(p_m).$$

This term introduces constraints by the a priori knowledge about the expected shape of the vessel tree projection and will penalize parameter configurations that might fit well with the data but that are very unlikely to reflect an existing imaging situation.

According to another exemplary embodiment of the method according to the present invention, a segmentation step to find the main branches in the angiographic image precedes the adaptation. It yields a measure of the center lines of successfully segmented coronaries called S. The subsequent adaptation is computationally less extensive, because no feature term has to be considered during the adaptation and no access to the image is required anymore. Instead of the image feature term $f_m(I)$ a distance measure $\delta_m(S)$ on the segmentation result is used: $\sigma=d_m+\delta_m(S)$. $\delta_m(S)$

determines the distance between $s_{b,l,\phi_m} \cdot M_{p_m}$ and the center line of the segmented coronaries in the image. This variant also allows to use different model candidates and to decide, which one fits best. There could bė for instance a model for left-dominant type and one for the right-dominant type.

Instead of a global measure for the whole coronary tree as those introduced above, also a part of the model representing a single branches or sub-trees may be adapted to an image. The position of such a sub-tree may be modeled statistically with respect to its parent branch. Thus, the given or previously estimated position of this parent branch may be used to predict the position of its desired sub-tree in the image.

Instead of using a set of template models, each with a given geometry, a deformable model is used that allows its geometrical parameters to be varied within a certain range of values. Once it is adapted to fit the available data, a geometric prediction 3D and even in 4D (space + time) is available for the whole coronary tree. The range of parameters is determined by the modeled statistical distribution of the parameters, but also by the result of the feature term $f_m(I)$ applied to the image – or $\delta_m(S)$ applied to the extracted center lines respectively.

Thus, the model may be adapted to an individual image wherever evidence is sufficiently available from the image. In image regions where evidence given by $f_m(I)$ is low, a priori information d_m from the model is dominating the adaptation result. This advantageous property of the model and the application of the model in accordance with the present invention allows a well-founded estimation of branch position taking into account available knowledge about proximate branches. In the same way, a trajectory of a branch in time may be predicted from one or more images taken at different heart phases. The geometry at an unknown heart-phase may be estimated from the model taking into account available data from those heart phases for which images are available. Thus, advantageously, for example, patients with chronic total occlusions (CTO) in coronary arteries, the whole vessel branch beyond the CTO is usually not visible in angiographic images, because no contrast agent is transported there, can be diagnosed more accurately and easily.

Fig. 6 shows a flow-chart of another exemplary embodiment of a method according to the present invention. This exemplary embodiment of the present

invention is in particular suited, for example, for diagnosis of CTOs in coronary arteries where the whold vessel branch beyond the CTO is usually not visible in angiographic images because no contrast agent is transported there.

The two-dimensional images of angiographic images makes it hard to the cardiologist to predict the position and extent of coronaries. It is especially hard to differentiate an occluded ending (CTO) from an ending that extends further but orthogonal to the image plane. Reasoning and comparison of several projections from different angles is usually required with this kind of differential diagnosis. Therefore, a CTO may easily be missed unless it is explicitly suspected and all potential image positions are scanned by the observer. This situation may be improved by this exemplary embodiment of the present invention depicted in Fig. 6, where a simulated projection of the coronary tree is shown to the user together with the angiography. Due to this, a CTO case becomes obvious by a branch indicated as missing. This will be described in further detail with reference to Figs. 6 and 7.

Steps S1 to S7 of Fig. 6 correspond to steps S1 to S7 in Fig. 2 and thus, to avoid unnecessary repetition, reference is made to Fig. 2 for the description of steps S1 to S7.

In contrast to the method of Fig. 2, from step S7, the formally three-dimensional model, which has been adapted to the image acquired in step S1, i.e. which has been adapted to feature in the images acquired in step S1 and which has been projected into the image plane of the image acquired at step S1, is overlaid in step S10 onto the image acquired in step S1 (an interruption of the adaptation circle of steps S2 to S7 to branch off to step S10 may be decided in step S3 when a sufficient similarity has been reached). Then, the image is displaced in step S11 to an observer. Due to this, the image visualized in step S10 shows the coronary tree or the respective arteries discernible, i.e. visible in the image and the overlaid adapted and projected model. Due to this, for example, a CTO case becomes obvious by a branch indicated by the model, but missing in the image.

This is depicted in Fig. 7. Fig. 7 shows three different images generated in accordance with an exemplary embodiment of the present invention. The first image indicated in Fig. 7 by *a* shows a main artery (black), which is clearly visible in the image. However, as may be taken from image *a*, a proximal part of a coronary vessel

tree is visible in this angiographic image (black) and a distal part, which is not visible in the angiographic image and which lies beyond a total occlusion is predicted by the model (white). As may be taken from image *b* in Fig. 7, the main branch has an occlusion and would usually not be visible in the angiographic image. However, the occluded part of the main branch is indicated by the model. Image *c* shows a functional occlusion.

In other words, for CTO diagnostic imaging, the model is adapted to an angiographic image in the way explained above. A simulated projection of the model is then overlaid with the angiographic image. A fused visualization of a measure (the image) and the expected normal finding (the warped model) immediately allows the cardiologist to diagnose a CTO (see Fig. 7) at positions where a predicted branch is missing in the image. Especially in screening situations and in cases without previous indication of CTO, it appears hard to visually scan all relevant positions. By using the present invention as indicated above, finding CTOs may be significantly facilitated because differences catch the eye.

The above explained exemplary embodiment of the present invention may, for example, also be applied in conjunction with catheter intervention, where a catheter is to be navigated through the vessel to an occlusion. In particular, in cases such as depicted in image *a* (Fig. 7), it is usually hard to find the entry point of a side branch having an occlusion, since the side branch itself is not discernible in the measured image. The visualization of the predicted position, as shown in image *a* (Fig. 7), allows an improved navigation of the catheter.

Fig. 8 shows a flow-chart of another exemplary embodiment of a method according to the present invention. As steps S1 to S7 of the method depicted in Fig. 8 correspond to steps S1 to S7 of the method depicted in Fig. 2, reference is made to Fig. 2 for a detailed description with respect to steps S1 to S7.

After a sufficient similarity has been reached, (which may be determined in step S3) the method may continue from step S5 to step S21. In step S21, branching off from step s5, a prediction is made by calculating projections of model positions for other heart phases φ and other projection angles p. Then, in the subsequent step S22, the warping parameters are determined and applied for overlaying images, which may allow for an image enhancement. The operation performed in steps S21 and S22 will be

described in further detail in the following:

During an angiographic intervention usually a couple of images is taken from slightly different angles. These images can be superimposed to each other in order to enhance the signal of a given object of interest with respect to the noise level if corresponding positions and orientations of this object are known in the different images. Here, the correspondence is established via the coronary model. Corresponding positions and orientations are available and local image registration could be achieved. The projection of a sample point of a given branch b_g is given by $s_{b_g,l,\phi_m} \cdot \boldsymbol{M}_{p_m}$ where all model parameters are adapted to the image. These corresponding image positions are used to achieve a landmark-based registration between all the images. In order not to superimpose images from largely different viewing angles, only projection with low differences in p_g - or p_m respectively - should be chosen. The superposition of a line in the images that is expected from the adapted model to be the location of a branch makes the branch visible even though it was not clearly visible in the single images alone. This should work for smaller sub-branches that are hardly detectable and for the case of functional occlusion (Fig. 7) where only a certain amount of contrast agent is transported to. But this technique is even promising for totally occluded branches as it also enhances the poorly visible vessel wall. The true benefit from the model-based approach comes by aligning the model to the visible parts of the coronary tree and predicting the position of not sufficiently visible parts from that.

According to exemplary embodiments of the present invention, a model of the coronary artery tree is adapted to the coronary artery tree visible in a measured image. The estimated position and orientation of cardiac structures reflected by the model may, according to an exemplary embodiment of the present invention, be used to calculate a set of parameters, for example, for the x-ray equipment. Such set of parameters may include position and orientation of x-ray generators and detectors in order to produce the cardiac standard projection image or in order to achieve an optimal x-ray set-up to image a given coronary artery. Furthermore, an iso-center for rotational cardiac x-ray imaging may be determined according to this exemplary embodiment of the present invention. By continuously feeding generated images during the examination to the model registration method, the accuracy of the adapted geometric model and the estimated position and orientation of the cardiac structures improve

further, especially if additional structures (for example, additional coronary arteries) are imaged.

Advantageously, this may allow for a very accurate setting of the x-ray equipment and a reduction in the x-ray dose applied to the object of interest, i.e. the patient. This may also allow to reduce the amount of contrast medium applied to the patient.

In spite of the fact that the present invention was described above with reference to the human heart and the determination of a coronary artery tree of the human heart, it is obvious to the skilled person that the above described present invention may also be applied to moving objects in general. In particular, the present invention may be applied to the determination of structures of a moving object from two-dimensional data sets, where, for example, the data set comprises images taken from different projections or taken at different points in time.